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STEAM BOILERS, POWER-GENERATING FUEL, BURNERS, AND BOILER AUXILIARY EQUIPMENT

Pneumatic Transportation of Dispersed Medium through a Vertical Tube Immersed into a Fluidized Bed

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Abstract—We discuss the technical problem of how to transport granular material in a vertical direction from the underlying section of a multistage apparatus containing a fluidized bed to an upper section through tubes immersed into the fluidized bed without additional expenditures of energy. The intensity with which the dispersed medium (a mixture of gas and fuel particles) moves through the tube and the mass flowrate of particles are determined by the ratio between the hydraulic resistances of dispersed medium inside the tube and of the fluidized bed outside of it. In turn, this ratio depends on the fluidization number W ($W = w_s/w_0$, where w_s is the seepage velocity and w_0 is the fluidization commencement velocity) and on the tube immersing depth into the bed.

Keywords: dispersed medium, fluidized bed, pneumatic transportation, solid particles, fluidizing agent, bed porosity, hollow cylinder (tube)

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Overflow devices serving to transport solid particles from upper sections of a multistage apparatus to its underlying or neighboring sections are an important structural element of such equipment. The task the authors of this article set forth was the inverse one: to reveal whether it is possible to transport solid particles in the opposite direction, i.e., from an underlying section of the apparatus to its upper section without additional expenditures of energy. Such a task is stemming from the following experimentally established fact [1]: if a hollow cylinder is immersed into a fluidized bed, the height to which dispersed medium ascends inside this hollow cylinder is larger than the height of fluidized bed in the apparatus.

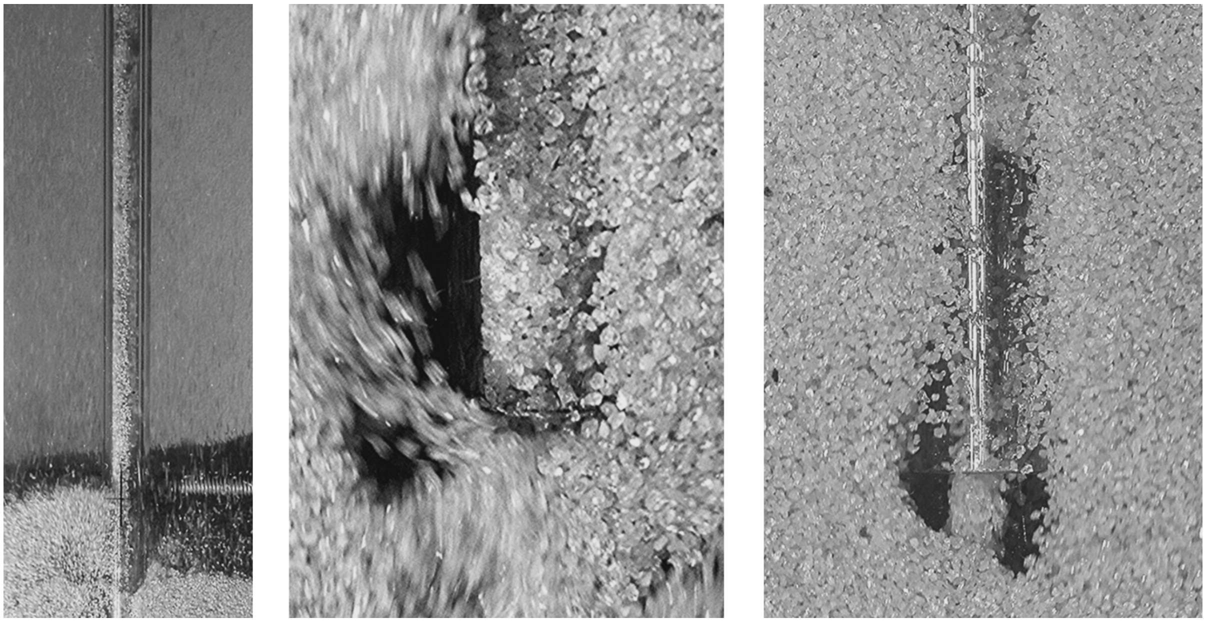
In [2], a pattern in which gastight vertical cylinders immersed in a fluidized bed are streamlined was described. However, the way in which a fluidized bed flows over a hollow vertical cylinder differs from the way in which it flows over a gastight cylinder. With a gastight cylinder, the bed porosity and gas velocity tend to increase near the cylinder's outer surface, whereas in a hollow vertical cylinder conditions are created for intense pneumatic transportation of the solid phase inside of the cylinder itself.

The purpose of this work is to describe the transportation of dispersed medium through a tube immersed vertically into a fluidized bed, to explain this phenomenon, and to elucidate the factors influencing the flowrate of solid particles flowing out through the tube top section.

EXPERIMENTAL RESULTS

A fluidized bed was created in an apparatus with rectangular cross section 0.15 × 0.15 m. Particles of spherical and irregular shape with equivalent diameter d_p from 0.13 to 1.15 mm were used as a solid phase, and air was used as a fluidizing agent. A perforated grate with a live section (i.e., a free section for air flow) equal to 9.82% served as a gas distribution device. This value is optimal in terms of power expenditures for fluidizing the bed of dispersed material [3]. A 1.5-m-long glass tube with the inner diameter D was secured in a vertical position at the apparatus center by means of two clamps allowing the tube to be moved along the bed height. A few different tubes with the inner diameter D varying from 1.5 to 24 mm were used in the experiments. The poured bed height H_0 was varied from 20 to 120 mm. To obtain a visual idea of how dispersed medium ascends in the tube, the process was recorded by means of a digital video camera at a frequency of 25 frames per second and by means of a camera with an exposure time from 1 to 10^{-3} s. The mass flowrate G of particles flowing out through the tube upper edge was determined using the weight method (the mass of particles flowing out through the tube for a preset period of time was determined by weighting them on electronic scales).

When a dense layer transfers into fluidized state ($W \geq 1.05$), fluidizing agent rushes at high velocity to inside the tube due to low hydraulic resistance of the tube inner cavity, and solid particles are intensely sucked from the space adjacent to the tube lower edge as a result of ejection. Dispersed medium moves



(a) (b) (c)

Fig. 1. Tube streamlined by a fluidized bed. The exposure time is 10^{-3} s. (a) Ascending of dispersed medium via a tube immersed in a fluidized bed, (b) streamlining of the tube in the period of its blocking, and (c) suction of solid particles from the gas cavity vault.

upward along the tube at high velocity. At $D/d_p < 15$, particles move upward as a continuous flow or in the form of slugs going one after another and occupying the entire inner section of the tube (Fig. 1a). At $D/d_p >$ 15, the solid phase occupies only part of the tube inner section.

As the amount of solid particles in the tube increases (i.e., as its inner cavity becomes saturated with them), the hydraulic resistance increases, the fluidizing agent velocity slows down, and concurrently with it the flow of solid particles decelerates and then comes to full stop. The tube is "choked;" its resistance first becomes equal to and then slightly higher than the bed resistance.

When the resistance of dispersed medium inside the tube begins to exceed the resistance of the bed outside of it, the fluidizing agent is no longer sucked, and particles are no longer ejected, and the tube lower end immersed in the fluidized bed becomes blocked. An excess pressure of gas begins to appear under the immersed tube end; the bed is deformed, and particles are driven away from the tube lower end. A pulsating gas cavity is formed, which occupies already the entire lower end's surface area, including the tube flow pass section. The pattern in which the medium flows over the hollow tube is for some period of time similar to that of a solid cylinder: the main flow moves at an angle to the lateral surface and is interrupted by thin pulsating air jets along the tube external side (Fig. 1b).

Under the effect of gravity force and in the absence of external lifting force, particle in the tube begin to descend, the resistance inside the tube decreases, and fluidizing agent again rushes to inside the tube, entraining particles from the gas cavity vault; the smaller the resistance inside the tube, the more intense the entrainment is (Fig. 1c). The gas cavity, which has occupied the entire space under the tube lower end by that time, pulsates, and as it collapses, gas from it also enters into the tube inner cavity, thus significantly enhancing the suction of particles from the space adjacent to the gas cavity. The mixture of gas and particles (a dispersed flow) ascends over the tube; the process is repeated again, and oscillations of dispersed medium take place in this way, the amplitude of which may be quite significant.

An increase of the tube lower end wall thickness δ has an effect on the gas cavity sizes both when it occupies the entire space under the tube end (in this case, the resistance inside the tube is higher than the bed resistance) and when fluidizing agent is intensely sucked to inside the tube and the gas cavity occupies only the tube end annular part (except with the central hole).

The dispersed medium ascending process described above is unsteady in nature; the fluctuations of medium in the tube depend on the intensity of gas cavity pulsations under the tube lower end and on the continuous variation of bed porosity in the tube wall zone.

Experiments showed that there are minimal and maximal inner tube diameters at which ascending of dispersed medium does not occur. These diameters are

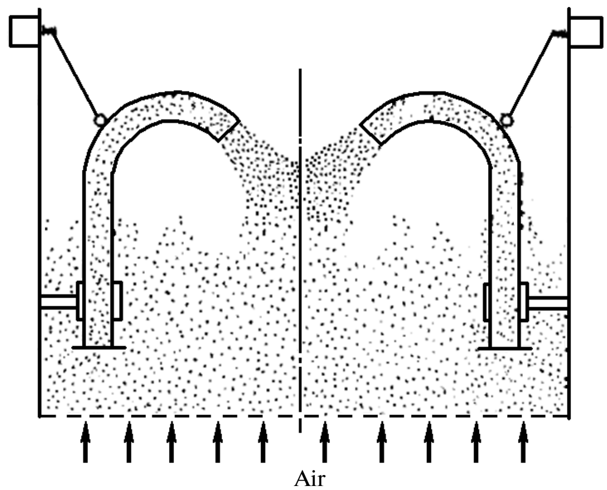


Fig. 2. Scheme explaining enhanced drying of dispersed medium by spraying particles above the fluidized bed surface.

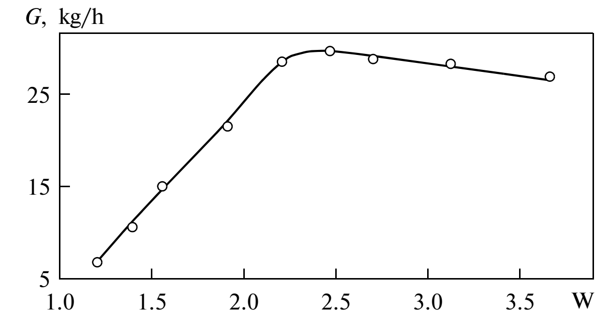


Fig. 3. Dependence of the mass flowrate of solid particles flowing out through the tube upper section on the fluidization number W (corundum is used as material, d_p = 0.51 mm, H_0 = 110 mm, h = 35 mm, D = 4.8 mm, δ = 4.5 mm, and the tube height is 0.35 m.

determined by the sizes of bed particles. Situations in which the height of dispersed medium in the tube exceeds the fluidized bed level are observed in the cases when $1 < D/d_p < 30$ for a bed composed of spherical particles and when $1 < D/d_p < 50$ for particles of irregular shape. The most pronounced effect is achieved if $D/d_p \approx 6–8$ and $D/d_p \approx 4–6$, respectively, for beds composed of particles having arbitrary and spherical shapes. If the tube length is smaller than the dispersed medium ascending height, intense spouting of particles takes place. Hence, if we fit the tube upper end with bent nozzles (Fig. 2) it will be possible not only to transport solid particles through the tube, but also to direct the dispersed jet (a flow of particles and air) to any place, for example, on the thermally processed surfaces of bodies floating in the fluidized bed [4]. We can also significantly intensify drying of particles without additional expenditures of energy by using fluidizing agent as transporting medium.

The general regularities pertinent to the motion of dispersed medium along the tube remain almost the same for the case when particles continuously flow out through its open upper end. The only difference is that fluidizing agent is sucked and solid particles are transported via the tube continuously (the tube inner cavity does not become saturated with particles because they are constantly removed), and that the pulsations of dispersed medium are smoothed out because the tube lower end is blocked only partially.

The dependence of flowrate G through the tube upper section on the fluidization number is shown in Fig. 3. As the fluidization number increases, the amount of particles flowing out from the tube increases first, then it stabilizes on reaching a developed fluidization mode (W = 2.0–2.5), after which the flowrate begins to decrease.

The maximum on the curve $G = f(\mathrm{W})$ (see Fig. 3) can be explained as follows. The hydraulic resistance of dispersed medium in the tube is lower as compared with that of the bed outside of the tube. As the seepage rate increases, so does the flowrate of air and particles through the tube. Concurrently, the bed porosity in the entire apparatus increases, and the hydraulic resistance decreases. As the seepage rate increases, the flowrate of dispersed medium moving in the tube increases and reaches a maximum. As this takes place, the resistance of dispersed medium in the tube (per unit area) reaches a minimum as compared with the resistance of the bed outside the tube. As the seepage rate is increased further, the hydraulic resistances and the air flowrates per unit area in the tube and in the apparatus become equal to each other, and, as a consequence, the height to which dispersed medium ascends in the tube becomes approximately the same as the fluidized bed height.

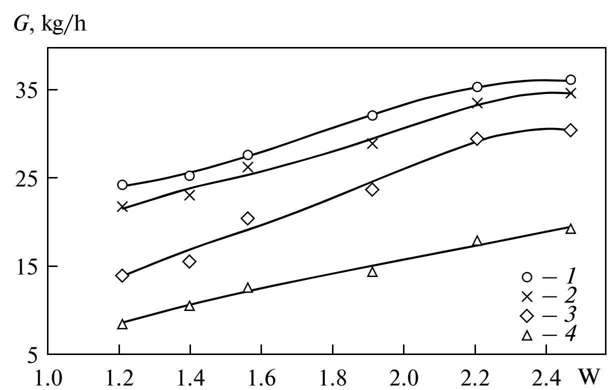


Fig. 4. Dependence of the mass flowrate of solid particles on the fluidization number at different distances h between the tube lower end and the gas distribution grate (H_0 = 110 mm, d_p = 0.51 mm, D = 4.8 mm, and δ = 6.6 mm). The points represent the experimental data and the lines represent the generalizing curves. h, mm: (*1*) 5, (*2*) 20, (*3*) 40, and (*4*) 60.

It has been found by experiment that the flowrate of particles flowing out through the tube upper end depends on the distance h between its lower end and the gas distribution grate (Fig. 4).

It follows from Fig. 4 that the flowrate of particles increases with increasing the depth to which the tube is immersed in the bed. This is because the bed resistance depends on the bed porosity, the value of which near a body immersed in the bed is higher than the porosity value averaged over the bed volume [2]. Hence, the air seepage resistance is smaller near the tube walls. As the distance between the tube end and the gas distribution grate decreases, the bed resistance outside of the tube increases (the bed height is larger), and the air flowrate through the tube increases, thus increasing the flowrate of solid particles through it.

As δ increases, so does the flow of particles moving inside the tube. This phenomenon is observed for a bed of particles having both spherical and arbitrary shapes. This is connected with the known fact [2] that a tube end of a larger size gives rise to a gas cavity of a larger volume. The air flow generated by this cavity entrains particles, thus increasing their concentration and motion velocity inside the tube.

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